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Energy Efficient and Reliable MAC Protocol for Intra-cluster Communication in Application Specific Wireless Sensor Networks

S. Lavanya[1] and S. Prakasam[2]

[1]Research Scholar, Department of Computer Science and Automation,
Sri Chandrasekharendra Saraswathi Viswa Mahavidyalaya -SCSVMV University,
Enathur, Kanchipuram - 631561, Tamil Nadu, India.

Orcid Id: 0000-0002-3008-0430

[2]Associate Professor, Department of Computer Science and Automation,
Sri Chandrasekharendra Saraswathi Viswa Mahavidyalaya -SCSVMV University,
Enathur, Kanchipuram - 631561, Tamil Nadu, India.

Abstract

Designing and developing an energy efficient and reliable protocol for many remote monitoring applications is a cumbersome task especially while handling multiple class traffics. According to the application demands, the chosen MAC protocol should be able to communicate the data without loss and at the required time. Low duty cycle MAC protocols lead to latency and high duty cycle leads to energy loss. So duty cycle adaption according to traffic conditions and data priority becomes necessary. Traditional MAC protocols were based on IEEE 802.11and by introducing the concept of active/sleep phase, adaptive listening and by changing the contention mechanisms, these protocols were made suitable for wireless sensor networks. This paper proposes a hybrid MAC protocol that could be used in an Intra-cluster communication. Simulation results shows that the proposed protocol EER-MAC uses both contention based method and a variable TDMA approach for sending data and is compared with various other MAC protocols namely the popular and the first duty cycle protocol namely SMAC, 802.11 EDCA and traffic adaptive event MAC namely EA-MAC. EER-MAC performs better than the other existing protocols in terms of packet delivery ratio, throughput, and control overhead.

Keywords: Clusters, Energy efficiency, Medium Access Control, Reliability, Sleep, Priority

INTRODUCTION

Reliable data delivery is the prime motivation for any application developed using Wireless Sensor Network (WSN). This objective is mostly achieved by developing a network that is reliable, energy efficient, scalable and achieves the necessary Quality of Service (QoS) requirement. Medium Access Control (MAC) provides easy access of the channel among various sensor nodes in a clustered network in a fair and efficient manner. A MAC protocol plays an important role in energy conservation, reliable packet delivery, avoids latency and provides QoS. The research on MAC protocol design is mainly needed for accurate data delivery. Many papers authored by [1-5] talk about MAC and its QoS requirements. MAC protocols are classified based on their channel access method. Some authors classify MAC as contention- based, contention-free and hybrid protocols. Authors [6-9] classify contention based MAC protocols further into synchronous and asynchronous. Few authors classify MAC protocols as schedule based, contention based and preamble sampling MAC protocols. SMAC [10-11] is the first MAC protocol that was designed to save energy by using a duty cycling approach. Many versions of SMAC protocols were developed further to decrease energy. Most of these protocols were designed for periodic data access. Very little literature survey is available for event driven WSN. In event driven WSN, nodes transmit reports only when events are detected. EB-MAC, ECR-MAC, SIFT MAC were all designed for event driven WSN. Application-specific MAC that needs to sense both periodic and event based data are seen very rare in literature. Very little MAC protocols are designed keeping in mind the QoS requirements.

In designing these applications, the sensor nodes are organised as clusters. Clustering approach is suitable than a flat layer as it ensures network scalability. Few to mention are some of the protocols such as LEACH, MCDA, TLPER, EADUC, CERP, TEEN, APTEEN and so on. A detailed survey on a number of clustering protocols, the method of cluster formation, criteria to select cluster head and method of communication within the clusters are discussed in detailed by the authors[12-16]

RELATED WORKS

A number of MAC protocols are available in the literature for detailed study on reliable data delivery. The main design objective of all the mechanisms mentioned by the authors has the main goal of maximizing lifetime of the network to send the data to the destination. Energy conservation is needed so that the system lifetime is increased. Preservation of energy is directly related to reliable data delivery. Authors [1,8,10] states the general techniques for energy preservation. These include periodic sleep/wake patterns, adaptive listening, collision avoidance, overhearing avoidance and message passing. A number of MAC protocols and their classification are explained in detail by authors [6-10].Commonly used synchronous protocols are S-MAC, T-MAC, R-MAC and

DW-MAC. B-MAC, WISEMAC, X-MAC and RI-MAC are some of the asynchronous protocols that are in use for most applications. Few protocols follow adaptive scheduling according to the traffic needs. Such hybrid protocols are studied in detail by authors [1-7]

Pqueue- MAC was proposed by author[2] that concentrates on energy consumption when events are not detected. It uses preamble sampling during low traffic conditions and TDMA for high traffic conditions.

A Priority based Cross Layer Routing Protocol was proposed by author [3] namely PCLRP and PCLMAC for health care applications for ensuring reliable data dissemination.

Author [4] speaks about MAC protocol for Body Area Network. Sleep-wake up cycle is used to save energy. The author [5] has proposed a transport protocol where apart from energy efficiency, consideration is also given to reliability by avoiding congestion. This paper talks about QoS requirement for achieving end-to-end reliability.

Priority-based QoS MAC (PQMAC) is proposed by author [6].Data priority levels are used to differentiate among data transmissions. They use advanced wake up schemes that leads to latency.

Author in [7] explains about Priority based Hybrid protocols (PHP) where an efficient architecture is used to save energy of sensor node and at the same time send emergency real time packets at appropriate time without delay. It uses hybrid models that use clock-driven, event driven and query – driven algorithms. It includes methods for congestion avoidance and provides flexible sensing period adjustments.

MAC PROTOCOLS FOR INTRA-CLUSTER COMMUNICATION

S-MAC:

Sensor MAC is the first and the popular contention based MAC protocol that uses periodic active/sleep phase to avoid energy loss. It is based on IEEE 802.11 CSMA/CA with wakeup/sleep phase to avoid idle listening caused due to channel contention. The analytical and simulation performance of SMAC with regard to throughput, latency, residual energy and reliable data delivery has been studied by various authors. SMAC frame is composed of SYNC period, active and sleep phase. The listen period is fixed, and the problem of collision is avoided by the use of RTS/CTS/DATA/ACK. SMAC works perfectly well under light traffic conditions as active time is fixed. But the residual energy of nodes affect the lifetime of network when there is difference in traffic flow. So sleep cycle is to be reduced.

The duty cycle of SMAC is given by Eq.(1)

Duty cycle = Active time/ Active time + Sleep time

….Eq.(1)

Low duty cycle means sleep time is more and energy is saved. But this happens only when traffic is low. Many improvements were made to SMAC based on adaptive duty cycle approach. High traffic implies the occurrence of the event and according to the traffic flow the duty cycle of node is modified by sending modified duty cycle to the neighboring nodes using SYNC message. This approaches works best as only few nodes change their duty cycle to high and others work in normal mode.

EDCA:

IEEE 802.11 EDCA[18] supports Qos demands of applications. It supports best effort traffic as it includes four access categories for different traffic flows. 802.11e makes use of VCM and HSAM as opposed to 802.11 DCF and PCF. Few enhancements were made to 802.11 DCF. Access categories are available that allows higher traffic to wait for shorter time by assigning less time for the contention window (CW) and shorter AIFS time. The access probability is set using different AIFS and CW values according to the traffic flow. To enhance the reliability of the system, frame concatenation with block acknowledgement scheme can be used. In 802.11e, each station may have data with different access categories and each would be given a chance to transmit its own data.

The main difference between 802.11 and 802.11 e is that the inter-frame space AIFS in 802.11e is not constant.

AIFS[AC] = SIFS + APV …..Eq.(2)

Where APV is the assigned Priority Value which is different for different AC

The minimum and maximum value of contention window (CW) also varies depending on AC. Therefore every access depends on TXOP, AIFS and CW time.

EA-MAC:

EA-MAC[19] follows node correlation and traffic adaptive flow control that works best in low and high traffic conditions. It classifies nodes that belong to a region and a representative node is chosen for data transmission. Value of duty cycle in EA-MAC is adjusted according to the varying traffic conditions. This is called adaptive duty cycle. It uses ARMA model for predicting traffic flow in the networks. This ARMA model is mainly used to predict periodic data flows. According to the traffic flows duty cycle and contention window are adjusted.

The following parameters are used in EA-MAC:

L – Threshold for lower traffic

H – Threshold for higher traffic

$[D_{min}, D_{max}]$ – Initial value of the duty cycle is set to 10%

f_{rate} – Flow of data

1. If f_{rate} <= L, then it indicates that the network traffic is low and so the listener time is reduced and duty cycle ratio is changed.

The new duty cycle ratio is given by

$$D_{new} = D\text{-lamba} * H / f_{rate} \quad \text{…. Eq.(3)}$$

2. If L< f_{rate} < H, traffic flow is moderate, so the usual duty cycle is used.

3. If f_{rate} >= H, then it indicates that the network traffic is high and the new duty cycle ratio is set as,

The new duty cycle ratio is given by

$$D_{new} = D + \text{lamba} * H / f_{rate} \quad \text{….Eq.(4)}$$

Here collision is avoided as new backoff is set.

EA-MAC uses CSMA/CA for channel access and exponential backoff is an important parameter.

Backoff is calculated using Eq.(5)

$$\text{Backoff} = \text{Random( )} * \text{xslottime} \quad \text{…..Eq. (5)}$$

Where xslottime denotes fixed timeslot and Random is a value that belong to [0,CW]. To adjust the contention window, the traffic flow is needed. When traffic is high, SYNC message is avoided to reduce control overhead.

Intra-Cluster Design for Application Specific Wireless Sensor Networks

The primary motivation is to develop an application specific MAC protocol where each node monitors both periodic and event based data. The underlying objectives in designing a scalable and reliable system can be achieved by using hierarchical clustering approach. The clustering architecture involves two stages namely cluster formation phase and data communication phase.

The following assumptions about the networks are made:

1. A set of sensors are distributed in a given area to monitor periodic and event based data.
2. All sensors are assumed to be homogenous and static.
3. The intra-cluster communication is of one hop distance and communication between the Custer Head (CH) and the Base Station (BS) is considered to be multi-hop communication.

A number of clustering techniques are applied. Formation of cluster is based on the hierarchical approach. The cluster formation is followed by data communication phase.

Data Communication Phase

After the cluster formation phase, data communication phase begins. The designed EER-MAC (Energy Efficient and Reliable) MAC protocol is application specific where periodic data is non-real time packet and event based data should be sent immediately to the BS as real time packets. Therefore priorities are set for critical event-based data packets. Packets containing periodic data are of low priority, so loss of such non-real time packets are acceptable. Threshold levels are set for real time packets and upon detection of these packets data is sent immediately without loss. The packet header contains an extra bit 1 set in its priority field as an indication that they are packet with priority and needs to reach the destination immediately. Appropriate queuing models are used in alleviating real time packet drop. Data communication phase ensures collision free transmission thereby ensuring reliability in avoiding retransmission and packet loss. This is achieved by applying CSMA/CA and vTDMA approach.

The objective of the proposed EER-MAC is to send prioritized real time data and non-prioritized periodic data to the destination without data loss and at the required time. To achieve this goal, the main decision making attributes are as follows:

- Threshold value of queue
- Packet priority

The general procedure is to send the event based data using CSMA/CA and the remaining packets can be sent using vTDMA using the information obtained from the queue.

Cluster Formation	Event data using CSMA/CA	CH to BS using	Periodic data using vTDMA	CH to BS using

Figure 1: Data communication phase in Intra-cluster communication

Every sensor node may have only one real time packet to send and not all nodes might detect the event. Therefore the chances of collision are less and CSMA/CA is used. The procedure is explained briefly below.

The data communication phase involves the following stages:

1. First the clusters are formed and the CM nodes are associated with some CH.
2. CM nodes sense the data and store it in their queues. The event based data is stored in the header of the queue and periodic data is stored in the tail part.
3. The Cluster Head(CH) signal for the communication to begin using a preamble. The CM that contains event based data in their queue is sent using CSMA/CA. Such event detection is very rare and mostly the data reaches CH without collision. Every CM is allowed to send only one data packet. If suppose the traffic grows owing to high event occurrence then the contention window size CW_{max} can be increased according to traffic needs by

analyzing the content of the queue. If still the data needs to be transmitted then the CM nodes start sending their data using vTDMA slots to the CH. Variable slots are allocated since some nodes may have pending data that could not be sent using CSMA/CA approach. These variable TDMA slots are allocated by the CH after analyzing the decision making attributes.

The CH aggregates both periodic and event based data based on the threshold values and sends the aggregated data to BS using suitable routing protocol. Hierarchical routing is followed where the data is sent hierarchical upwards to the CH that forwards it to the base station.

SIMULATION RESULTS

A simulation model is set up with network size of 500 * 500 with 100 nodes. The size of the packet is set to 512 bytes. The starting simulation time is set o 25 and simulated end at 150. The length of the queue is set to 50. The receiver power is set to 0.3mW and transmitter power is set to 0.6mW. Idle power is set to 0.2mW. The simulation is carried out at time 50, 100 and for 150 sec.

Performance metrics

Packet delivery Ratio (PDR):

PDR is defined as the ratio of packets successfully received to the total number of packets send.

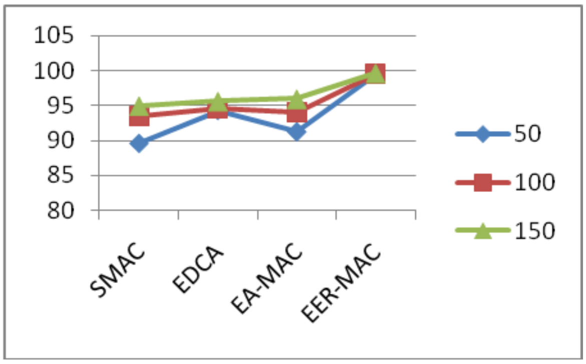

Figure 2: Packet delivery Ratio vs Simulation time

From the graph it can be seen that the PDR for S-MAC was 88.552 at simulation time 50 and at 150 it has raised to 94.8748. There was a gradual increase in PDR owing to sleep/listen cycle. 802.11 performed well and there was not much difference in the PDR as the time increases. EA-MAC has performed well during simulation time 100 and 150 since when the traffic increases, the contention window also increases allowing more traffic to flow through. The proposed EER-MAC protocol has a good PDR during simulation time 50,100 and 150 since packet priority is being followed allowing less packet drop and high packet arrival rate at the base station.

Control Overhead:

It is the ratio of number of control packets send to the number of packets delivered. From the graph it is very obvious that the control overhead increases as time increases.

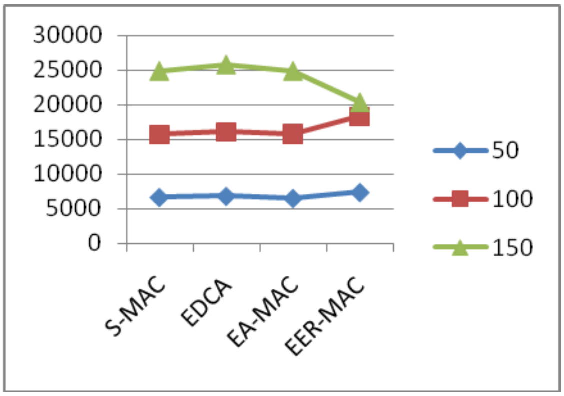

Figure 3: Control Overhead vs Simulation time

Delay:

It is defined as the average time for a packet to reach from source to sink. During simulation time 100, the nodes experience a severe delay during to network traffic.

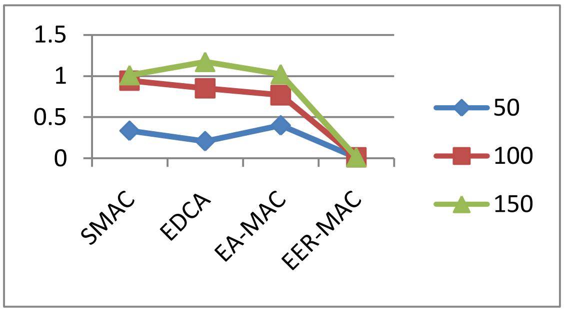

Figure 4: Delay vs Simulation time

Packet Drop:

It is the difference between the total numbers of the packets received to the total number of packets sent. The drop ratio is less in the proposed protocol when compared to the other existing protocols.

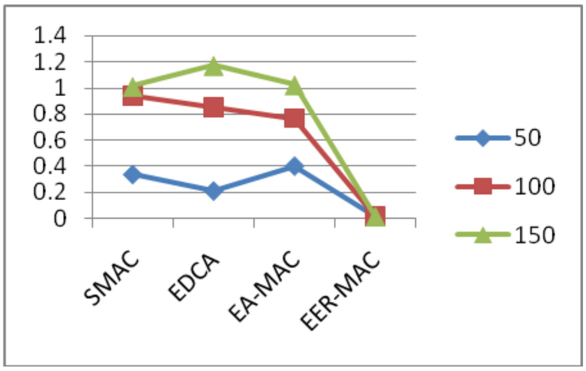

Figure 5: Packet Drop vs Simulation time

CONCLUSION

EER-MAC performed well when compared to the traditional S-MAC, EDCA CSMA access method and EA-MAC that followed an adaptive access pattern. EER-MAC is suitable when the application needs to handle multiclass traffic. EER-MAC tries to increase the packet delivery ratio and avoids packet drop as the prioritized data follow CSMA/CA pattern and according to the traffic pattern, the size of the contention window is also changed. The remaining data is send using vTDMA allowing critical data to be sent without loss. The periodic data follow event based data and delay of such periodic data doesn't affect the system performance at a greater level.

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